Assessment of Partial Discharge and Electromagnetic Interference On-Line Testing of Turbine-Driven Generator Stator Winding Insulation Systems
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EPRI Project Manager
J. Stein
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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Dr. J. Keith Nelson

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This report was prepared by

Dr. J. Keith Nelson,
2329 Knolls View Drive
Niskayuna, NY 12309-2205

Principal Investigator
J. Nelson

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Partial discharge (PD) and electromagnetic interference (EMI) on-line testing have been promoted as means to assess the condition of turbine-driven generator stator winding insulation systems. Such test approaches offer clear advantages in avoiding prolonged generator shutdown for off-line tests and inspections. Although PD is a time-domain measurement and EMI measures activity with a frequency scan, both techniques still evaluate the same phenomenon—high-frequency currents that flow as a result of electrical (partial) discharges occurring within the structure. This report documents assessments of the stator winding insulation condition for three generators—obtained by commercial test companies using PD and EMI techniques. It presents the results of these assessments and an appraisal of the effectiveness of each technique. The report should be read in conjunction with an earlier EPRI report, Partial Discharge On-Line Testing of Turbine-Driven Generator Stator Windings (1001209, December 2000), which provided a detailed primer on the mechanisms of machine deterioration and the installation of sensors for detection of discharge activity.

Results & Findings
Clearly, the greatest generator operator benefit of either a PD or EMI analysis is the ability to examine the degradation of a unit with respect to a baseline signature. Assessments documented in this report cover a 30-year old Westinghouse generator (800 MVA, 20 kV, H2 cooled) at Sammis Unit 6 of Ohio Edison (now FirstEnergy Corp.) as well as similar GE generators (790 MVA, 24 kV, H2 cooled) at Units 3 and 4 of the Marshall Plant of Duke Energy Corporation. Key findings include the following:

- It is not always easy to acquire unambiguous information from signatures available at machine terminals since such signals are often corrupted by noise. Perhaps the most effective way to reduce noise is to use two sets of couplers per phase and then apply time-of-flight methods to discriminate against pulses entering from outside the machine.

- Other useful techniques for reducing noise impact include setting a threshold for PD counting and establishing a background frequency scan to identify FM broadcast stations. Furthermore, an acoustic scan of the bus ducts can detect noise and would seem to be a quick and worthwhile additional test.

- Discharge characteristics are known to change as a result of both loading and power factor changes. Systems able to monitor activity over a period of time in which such changes take place clearly add another dimension to the diagnostic process.
Challenges & Objectives
The goal of this research was to contrast and compare the effectiveness of PD and EMI techniques for on-line testing of turbine-driven generator stator winding insulation systems. One key challenge arose with the fact that PD measurements in inductive equipment are very difficult to calibrate, and comparison between measurements made with different equipment, gain settings, filters, and couplers are highly problematical. However, comparative measurements—taken either between phases or at different times using the same equipment and settings—are meaningful to assess technology performance and appropriate applications.

Applications, Values & Use
This report provides not only a detailed account of test results but also an appraisal of the various methods employed. The project was designed not to compare the performance of testing companies but rather to objectively evaluate the capabilities of PD and EMI techniques for stator winding insulation assessment. By this means, EPRI hopes that the industry may be able to identify best practices for insulation condition monitoring and develop a formalized method of applying decision criteria. The program is still seeking to add to the test inventory a suitable air-cooled machine, characterized by a larger discharge signature and thus less pronounced noise interference.

EPRI Perspective
Both PD and EMI signatures are complex and often difficult to interpret, particularly in the case of measurements in the frequency domain, where the interpretation of results depends critically on the experience of the individual taking the measurements. To some extent, testers select indices to describe the characteristics or severity of the condition being investigated. Breakdown of the characteristics into meaningful parameters is a valuable and necessary first step on the road to greater use of computer-based intelligence in problem diagnosis. This report takes that first step in the field of generator stator winding insulation systems.

Approach
One tester evaluated the Sammis Unit 6 stator winding insulation system using installed 1000-pF couplers in the frequency range of 3 – 150 MHz. Assessment was made principally on the basis of a pulse height analysis with polarity discrimination. Another tester evaluated the unit using the EMI technique. Three companies tested the Marshall units’ insulation systems using PD detection, and two employed EMI in the frequency domain. In addition, one tester provided an acoustic evaluation of the isophase bus area using a hand-held ultrasonic probe to screen for major sources of electromagnetic noise that could prejudice on-line electrical measurements. All commercial testers contributing to this study obtained PD or EMI data and then applied engineering judgment to the phase-resolved pulse counts or spectral results. Their time-honored yardsticks for evaluation included polarity predominance, phase angles of discharge groups, frequency bands involved, and evidence of cross coupling.

Keywords
On-line monitoring
Partial discharge
Electromagnetic interference analysis
Generator stator winding insulation system
This report describes work that is a continuation of previously published work [13]. The insulation condition of three generators has been assessed by a number of commercial testing companies using both Partial Discharge (PD) and Electromagnetic Interference (EMI) techniques. The results of these assessments are presented and an appraisal of the techniques based on the results obtained is provided.
ACKNOWLEDGEMENTS

The need to maintain the anonymity of the Testing Companies does not allow the author to properly recognize those individuals whose work is here being presented and reviewed. That is regrettable, but it is hoped that those involved would accept the gratitude which is due to them since this project relies on their co-operation and goodwill. Thanks are also due to Mr. Jan Stein of EPRI who has both championed the project and done much to facilitate it. Finally, the help and cooperation of the utility engineers at the host sites, Mr Myron Horton and Mr. Terry Hitchcock and the advice of Mr. Clyde Maughan is also gratefully acknowledged.
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1 BACKGROUND

This report represents the continuation of ongoing EPRI work to provide an appraisal of Partial Discharge (PD) and Electromagnetic Interference (EMI) as techniques for assessing the condition of the insulation systems on large generators. This document should be read in conjunction with the earlier report [13] that provided a detailed primer on the mechanisms of deterioration in machines and the installation of sensors for the detection of discharge activity. The previous report also briefly documented the assessments made by a number of testing Companies on a 30-year old Westinghouse generator (800 MVA, 20 kV, H2 cooled) at the Sammis plant of Ohio Edison (now First Energy Corp.) from which the basic characteristics of the techniques were tabulated.

The Sammis unit #6 is still being monitored in this program, and two units at the Marshall Plant of Duke Energy Corp. which are similar GE water cooled units have been added. This report provides a detailed account of the results of these tests, and also attempts to provide an appraisal of the various methods employed in the light of the results obtained. It is not the purpose of this project to compare the performance of testing Companies, but rather to objectively assess the abilities of the various techniques used. By this means, it is hoped that the industry may be able to identify “best practices” in this area of condition monitoring. The scope is being expanded to look not only at the effectiveness of the basic methods being used, but also to try to start to assess the extent to which computer-based intelligence can assist in the interpretation of the results obtained. This is considered an important aspect since, at present, the interpretation of the results still requires the expert eye of seasoned engineers with considerable experience. These individuals are not numerous, and it is projected that future generations of PD and EMI equipment will rely increasingly on the automatic detection of problems from discharge signatures.

The program is still seeking a suitable air-cooled machine to add to the inventory. Generally, air-cooled machines are characterized by larger discharge signatures and thus may be seen as “easier” in the sense that noise interference issues are less pronounced. However, since there are numerous such machines on the system, and one of the objectives (see Section 5 below) is to assess how tests at different frequencies compare in a variety of circumstances, then the inclusion of such a unit would seem important.
There has been some repeat testing conducted on the Sammis #6 unit with both PD and EMI techniques. However, since the unit appears stable, most of the effort in 2001-2002 has been diverted to units #3 and #4 at the Marshall Steam Plant. Table 2-1 outlines the tests conducted on these units.

![Figure 2-1](image)

**Figure 2-1**
Evidence for bar looseness in the Marshall #3 unit. (a) Dark deposits around the slot exit regions. (b) Greasing on the slot wedges.

**Table 2-1**
Matrix of Tests Conducted

<table>
<thead>
<tr>
<th>Testing Entity</th>
<th>Sammis #6</th>
<th>Marshall #3 and #4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EMI</td>
<td>PD</td>
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<tr>
<td>A</td>
<td></td>
<td></td>
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<td>B</td>
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<tr>
<td>F</td>
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</tbody>
</table>
The history and details of the Sammis #6 unit have been given in the previous report. The Marshall units #3 and #4 which have recently been added to the program are General Electric H$_2$-cooled machines rated at 790 MVA, 24 kV Y-connected. The units were commissioned in 1969/70 and both had field rewinds (#3 in 1999 and #4 in 1994). The #4 unit had been partially rewedge in 2001. The units are both base loaded and have been under PD surveillance by Tester A since 1998. They were selected since there is a history of enhanced partial discharge activity, and a limited inspection carried out in December 1999 had indicated both deposits at the slot exit regions and “greasing” on the slot wedges at various locations (unit #3). Both these symptoms would suggest that the bars might be loose. The evidence is shown in Figure 2-1 (a) and (b). (The “greasing” reported is probably the result of oil contamination combining with abraded stator bar conductive coating to form a conductive grease.)

Figure 2-2
Coupler attached to isophage duct (Marshall #3).

Figure 2-3
Schematic diagram of coupler connections at the Marshall steam plant.
Both units are fitted with couplers (Adwel Model #M00150) inserted into the isophase bus at a position which is about 10 m from the generator bushings which is less than ideal. The couplers consist of a 1 nF, 30 kV capacitor coupled to a high-frequency current transformer and are depicted in Figure 2-2. in housings which are welded on top of each phase of the duct. Only one coupler per phase was available making it impossible to discriminate against external discharges by time-of-flight methods. However, the machines have 36 stator slots which also contain RTD sensors for temperature measurements with connecting wires in spiral armored conduit. These have also been used as PD detectors. The outputs from the couplers on all three phases are brought out via RG-58 coax cables to a common terminal box together with a reference signal derived from the Phase A metering potential transformer (500 mA fused). The schematic diagram is shown in Figure 2-3. which shows the way in which the high-frequency current transformers are coupled in the ground leads of the capacitors, and the terminal box depicted in Figure 2-4.

![Coupler terminal box.](image)

As an alternative, Tester F used a high-frequency current transformer which was placed around the primary return connection to the neutral grounding transformer as illustrated in Figure 2-5. The preferred placement on the high side of this winding could not be used since the angle of attachment of the bare wire from the neutral disconnect switch did not allow it. The use of a split core current transformer makes connection very straightforward and convenient permitting measurements to be taken without interruption to normal operation. However, unlike coupling to the line end of the windings using individual high-voltage capacitors, this technique does not readily allow problems to be identified with a particular phase which is a significant disadvantage.

Since the generator units are base loaded, they are usually running close to their nameplate rating and thus there was no opportunity to vary the load during on-line tests. By the same token, the technique of using the import or export of reactive power was not employed during any of the tests. This has been shown [1] to be a very effective way to identify machines with deteriorated groundwall insulation even if previous baseline measurements are not available.
Figure 2-5
High-frequency current transformer placement on the neutral grounding transformer.
3 TESTING: SAMMIS UNIT #6

During the last round of tests, there was considerable agreement among the testing companies using both EMI and PD methods [13] that the PD activity was in a range typical for this type of machine and insulation system. Since there were no signs of significant discharges in the slots, the slot exit regions or the end windings, only two testing companies were asked to assess this machine on this round of testing.

3.1 PD Assessment

Tester B evaluated the Sammis #6 unit (a 30 year old unit that was 100% rewedged in 1998) in November 2001. The tests were carried out through the installed 1000 pF couplers in the frequency range 3 - 150 MHz. In a comparative sense, these measurements should be classified as in the high frequency range.

Assessment was made principally on the basis of a pulse height analysis with polarity discrimination. The attributes used for interpretation were:

- The maximum value of the discharge pulses seen (in mV) usually above a given threshold such as $Q_{\text{max}}$ illustrated in Figure 3-1.
- An integrated measure taken from the area under a pulse height analysis curve, such as illustrated in Figure 3-1.

Figure 3-1
Schematic representation of some of the measures used to assess PD characteristics.
- The polarity predominance of the discharges.

Although individual definition of these measures varies slightly between testing entities, Figure 3-1 indicates the principle involved. It should be recognized, however, that PD measurements in inductive equipment are very difficult to calibrate, and comparison between measurements made with different equipment, gain settings, filters and couplers are highly problematical. However, comparative measurements taken either between phases or at different times using the same equipment and settings are meaningful. An example of this is shown in Figure 3-2, which shows comparative pulse height analysis measurements of Phase B of this machine taken by Tester B in 1999 and 2001. The difference between the readings taken at these two dates is not sufficiently significant to conclude any significant additional deterioration has occurred on the basis of the criteria above. Phase B was chosen since it is the worst phase. When judged either by magnitude or integrated energy, the other two phases present with less PD activity.

![SAMMIS UNIT #6 PULSE HEIGHT ANALYSIS](image)

**Figure 3-2**

On the basis of a lack of a clear polarity predominance, Tester B has concluded that the groundwall insulation (the compacted insulation between the conductors and the slot wall) is the likely source of the modest discharge activity.

### 3.2 EMI Evaluation

This unit has also been evaluated by Tester E using the EMI technique. It is understood that the methods utilized by both Testers E and F are essentially very similar. The resulting spectrum will have a structure which is often dominated by the resonance generated by standing wave patterns set up in the windings. This will clearly depend on the geometry and configuration of the winding (particularly its length, but also end winding geometry, etc.). There may also be sharp peaks corresponding to external sources within the frequency band investigated (broadcast transmitters, power-line carriers, etc). Discharge activity seen by this method can be interpreted by the skilled engineer from the frequency bands in which activity is seen and from the fine structure of the spectrum. In order to assist with this interpretation, a variety of detectors are often used which can measure the peak of the signal, a quasi-peak (with defined time constants).
or an average. All these detectors have been used at Sammis, and the example of Figure 3-3 shows the peak readings.

![Graph showing frequency vs. signal](image)

**Figure 3-3**

Figure 3-3 provides peak data for years 2001 and 2002. Unfortunately, the timing of the measurements does not correspond exactly with the PD measurements displayed in Figure 3-2. However, it can be concluded from Figure 3-3 that the machine appears stable (which was also the conclusion drawn from the PD measurements of Figure 3-2). Not only is there little change between the readings, but the levels of discharge in the frequency range below about 500 kHz, which may be due to the stator slot area, are modest and present little concern. The use of a high frequency current transformer in the neutral connection does prevent any phase discrimination.
4
TESTING: MARSHALL UNITS #3 AND 4

Table 2-1. indicates that the Marshall plant was tested by 3 entities using PD detection and 2 using the frequency domain approach. However, in addition, Tester D provided an acoustic evaluation of the isophase bus area. This was done using a hand-held ultrasonic probe (see Figure 4-1.) used to screen for major sources of electromagnetic noise that could prejudice the on-line electrical measurements. Several locations along the bus ducting showed levels of airborne noise characterized as “high” (~28 dB at 41 kHz for unit #3, and ~28-32 dB at 43 kHz for unit #4). However, since these emissions were below the typical acoustic frequency band of interest, it was considered of no consequence and no further action was taken.

Figure 4-1
Acoustic monitoring of isophase bus sections.

The plots which appear in this report are computer generated. As a consequence, the scales can change dramatically. The reader is cautioned to take particular care to reconcile the scale of the magnitude axis with the conclusions drawn.
4.1 PD Evaluation: Marshall #3

4.1.1 Testers A and D

Figure 4-2
Marshall #3 PD data (using Phase A for synchronization) in the frequency range 40 - 800 kHz. (a) Tester A, (b) Tester D.
Tester A has conducted PD measurements using pass-band amplifiers to select two different frequency ranges (40 – 800 kHz and 2 – 20 MHz) and undertaken phase-resolved PD measurements to generate phase/magnitude/count 3-dimensional surface characteristics to characterize the condition of the machine. These measurements should be classified as in the low frequency domain. Essentially the same equipment was employed by Tester D, which provides a useful point of comparison, especially since the two Companies took readings within 2 days of each other at very similar levels of load (707 MW for Tester A and 708 MW for Tester D) using the same couplers. As a consequence, they will be reviewed together. Comparisons are shown for the frequency band 40 – 800 kHz in Figure 4-2, and for 2 – 20 MHz in Figure 4-3. However, comparisons should be made with care since Figure 4-2(a) provides polarity discrimination whereas Figure 4-2(b) does not. Most discharge detection systems incorporate some deadtime (~5µs) so that only the initial pulse is counted and subsequent ringdown is ignored. Furthermore, the scales, although similar, are not identical. In particular, attention is drawn to the fact that Tester A has changed the gain between phases (by a factor of 10 in Figure 4.2(a)), so inter-phase comparison must be made with care. Although both Testers are providing scales indicating units of charge, it is not clear that either are actually truly calibrated [Tester B claims that readings are calibrated, Tester D admits that they are not]. Consequently, one is here looking for patterns rather than absolute magnitudes (see previous comment on the calibration of inductive equipment).
Several observations can be made from these measurements:

- Figure 4-2 (the lower frequency band) would indicate that both Testers depict similar signatures and PD order of magnitudes for Phases A and C.
- Both Testers depict a characteristically different discharge pattern in Phase B at a higher magnitude (Figure 4-2).
• In the high frequency band (Figure 4-3), both testers are indicating that two groups of discharge are present. The high level discharges are centered about the 0° and 180° angles in both tests, but the Testers are showing different phase relationships for the low level discharges.

• Both Companies are indicating discharges of very large magnitudes (in excess of 1 µC [uncalibrated]. Setting aside the question of calibration, these magnitudes are judged on the basis of databases maintained by the Testers (Tester A has a database of 100s of units and Tester D 10s of entries). Providing that proper account is taken of the couplers, gain settings, etc., this is certainly a legitimate way of scoping machines of similar construction and ambient atmosphere.

• The similarity of the phase resolved patterns in all 3 phases depicted in Figure 4-2, strongly suggests that discharges on one phase are being coupled to the other two phases. Based on the location of the pulses on the 60 Hz waveform, the results suggest that Phase C is the origin of these strong signals based on the identification of the discharges on the rising portion of each half cycle. In this context, the absence of polarity information is seen as a slight disadvantage since checks would then be available on the polarity of the discharges with respect to the 60 Hz wave.

• The finding of both these Testers that two regimes of discharges prevailed, strongly suggest two sources of activity. The low level activity may be normal internal groundwall degradation.

While Testers A and D both identified the abnormally large discharge activity, and cross coupling between phases, the interpretation was not the same. Based on the phase-resolved data, Tester D concluded that the source of the activity was surface discharges on Phase B (suggesting that these originated in the slots, the stress control paint or the end-turns). Tester A, on the other hand, reasoned that discharges of that level could not be sustained within a hydrogen atmosphere, and concluded that the source must be outside the unit (suggesting loose connections in the isophase bus duct, contamination of support elements, cracks in insulating materials, etc. as likely causes). It is perhaps pertinent here to recall that acoustic emissions were detected by Tester D in the isophase bus duct – see Section 4.0 above. In addition, Tester A concluded, on the basis of the patterns in Figures 4-2 and 4-3, that Phase C was the primary origin. However, the claim that discharges as high as 6400 nC in Phase C made by Tester A cannot be verified from Figures 4.2 and 4.3 since only discharges up to 1185 nC are plotted. Indeed, when the gain differences are accounted for, the magnitudes actually plotted would appear to be larger in Phase B. However, it is always possible that discharges were recorded on site beyond the scale of the plots given. The different identification of the faulty phase underscores the need for very careful identification and handling of the reference source (note the 30° phase shifts evident between Figure 4-3(a) and 4-3(b)). In Section 4.1.2, anomalous coupler identifications are cited by Tester C which may well be the root cause of this problem.
However, although the interpretations differ, much of the character of the measurements was independently replicated which is a very positive outcome.
4.1.2 Tester C

Tester C also undertook PD measurements in the frequency range from 1 – 20 MHz which would also generally be described as “low”. However, in addition to the use of the 1 nF couplers pictured in Figure 2-2., Tester C also was able to couple to the RTD temperature sensing elements built into the machine. This practice will be discussed later, but provides an important means to obtain some data on machines without any couplers attached. However, in this case the wire runs to the RTD terminal board were not the same for units #3 and #4 making any comparisons between the units only very approximate. In the absence of coupler calibration data, Tester C, like Tester D, has had to make assumptions in order to extract magnitude values for the PD tests. On the basis of typical coupling capacitor sensitivities (1 – 5 nC/V), a value of 5 nC/V was used since it was argued that an insulating gap in the bus duct between the coupler and the generator would have attenuated the received signals.
Testing: Marshall Units #3 and 4

Figure 4-6
Marshall #4 PD data (using Phase A for synchronization) in the frequency range 40 - 800 kHz. (a) Tester A, (b) Tester D.

Like Testers A and D, Tester C used the reference signal from the Phase A potential transformer as the standard synchronizing voltage. However, there are real questions regarding the labeling of the couplers based on the results obtained.

Tester C also provided a facility to record data over a period of about 20 hours for 15 PD signal channels (albeit with less resolution than available for spot measurements). The idea here is to detect changes in PD characteristics which may occur as a result of loading or the import or
Testing: Marshall Units #3 and 4

export of reactive power. These changes can be expected to alter the forces on the conductors which may change the PD behavior and provide clues as to degradation. Since these generators are base loaded, there was little change in real power during the period of the test. However, during the 20 hour period of measurement, the reactive power was changed by as much as 50%. This was not accompanied by significant changes in the PD characteristics measured by Tester C which would suggest that there was no gross looseness of the stator bars in the slots [1].

Figure 4-7
Marshall #4 PD data (using Phase A for synchronization) in the frequency range 2 - 20 MHz. (a) Tester A, (b) Tester D.
Figure 4-4. depicts the PD data for all three phases (without pulse polarity discrimination) and employs approximately the same frequency range used in Figure 4-3. Note, however, that, in this case, the phase angle is given on the Y-axis and the magnitude (here more correctly in mV) on the X-axis. The upper three plots in Figure 4-4. have a full scale of 5 V, whereas the display is adjusted in the lower traces to provide a full scale of 100 mV. [Note: This instrument has a single gain and dynamic range of 1 mV to 20 V. It is only the display that has been rescaled]. In this way, it has become clear that there are very high level discharges associated with Phase A, and also more modest activity on all phases. Tester C associates the very large discharges (shown with square boxes) with a loose bus duct supporting insulator, and the lower level discharges with more normal groundwall PD. Of particular interest are the discharges (shown circled) from coupler CCC that suggest that there may also be discharges in the end turns, close to the Phase B bushing.

For illustration, PD data taken by Tester C from the installed RTD sensors is shown in Figure 4-5. for the sensors at the non-turbine end of the machine. It is clear that some of these sensors are registering activity above the background noise, but, for the most part, there is no polarity predominance which suggests that most of this activity is confined to the groundwall (see later discussion on the use of RTD sensors for PD measurements).

Some of the characteristics uncovered by Tester C are common with the evaluations provided in Section 4.1.1. The common features are:

- The identification of activity at very high levels superimposed on more modest PD
- The finding of some cross-coupling between phases
- The detection of groundwall PD activity.

However, the identification of which Phases are involved is different which points to the need for very careful tracing and identification of the synchronization signals. Tester C has provided a Table which indicates that Couplers A, B and C as marked are not, in fact, the same phase sequence in this unit. However, it is probable that this determination was made by trying to identify the expected location of the discharges [~45° for negative pulses and ~225° for the positive pulses for the classic case in the slot portion of the winding]. However, discharges dependent on the phase-to-phase voltages will exhibit ±30° shifts which complicates this process, particularly if the polarity of the pulses is not being identified.

4.2 PD Evaluation: Marshall #4

4.2.1 Testers A and D

Analogous tests were conducted on Unit #4 at the Marshall Steam Plant. Figure 4-6 depicts the PD data in the lower frequency range, and Figure 4-7 in the range up to 20 MHz. Comparison of the low frequency data of Figure 4-6 does indicate some differences. Tester A is indicating that Phase C is generating significantly more activity than the other two phases, whereas the results shown in Figure 4-6(b) show little difference between the phases. The scales of these plots
Testing: Marshall Units #3 and 4

should also be noted since the levels in Figure 4-6 (a) and (b) are very different despite being taken only 2 days apart. Once again this points to the problem of appropriate calibration.

Figure 4-8
Marshall #4 PD data (using Phase A for synchronization). Tester C.

While, superficially, the patterns taken by Testers A and D at higher frequency shown in Figure 4-7 would appear rather different, there are in fact some important common features:

• In this frequency domain, both sets of measurements show levels of activity of the same order of magnitude. [Again note the change of gain used on Phase C by tester A in Figure 4.7(a)]

• There is clear evidence of phase-to-phase coupling (particularly in the intricate patterns in Figure 4-7(b)).

• Some modest groundwall PD is evident.

• Phase C is the source of the high level activity.

The Testers do again diverge on the interpretation of these patterns. Tester A again speculates that the high level activity on Phase C is likely to result from a source outside the generator at the isobars. Tester D interprets the cross coupling between phases as due to surface discharges, although expresses an element of doubt over the phase location of the discharges.
Figure 4-9
Marshall #3 EMI data in the frequency range 100 kHz – 500MHz. Tester D.
4.2.2. Tester C

Low and high gain phase-resolved PD are shown in Figure 4-8 for all three phases. The high level discharges (shown boxed on upper plot) are identified by Tester C as being likely caused by loose insulators in the bus duct (as in Unit #3). However, the phase-phase discharges so evident in Figure 4-7(b) are not so obvious in Figure 4-8. Nevertheless, Tester C does see enough evidence to identify the lower level discharges (circled in Figure 4-8) as resulting from end winding deterioration.

Measurements were also taken from the RTD sensors (not shown here) that indicated some activity in three of the slots at the turbine end of the unit. The clear predominance of activity in the positive half cycle has been interpreted as indicating a possible deterioration of the stress grading tape in the slot area or at the slot exit.

4.3 EMI Evaluation: Marshall #3

4.3.1 Tester D

Measurements in the frequency domain have also been conducted by Tester D (see Table 2-1) in the range 100 kHz to 500 MHz. Results for all three phases are shown in Figure 4-9 which includes both peak and averaged results. The latter can be useful in identifying non-stochastic sources such as radio stations and power line carrier frequencies in use. Included with the Phase B data is the output from an antenna so that the baseline radiated noise can be estimated.

Examination of Figure 4-9 indicates that there is a part of the spectrum at the very low frequency end (100 – 300 kHz) where Phase B shows a substantially greater activity than the other two phases. Tester D associates this with surface discharges in Phase B, although does not provide any reasons for this. Figure 4-9 also allows the identification of the areas of the complete spectrum which indicate the peaks of activity: 880 kHz, 4.17, 14.55, 16.5, and 50.27 MHz. Tester D can then use these identified peaks as center frequencies to filter the signal in a PD test. Such a “combined” analysis, if applied with care, may be able to improve the sensitivity of detection. In the case of Marshall Unit # 3, peak PD activity at about 16.5 MHz was confirmed.

Figure 4-10
EMI Spectrum for Marshall Unit 3 taken by Tester F.
4.3.2. **Tester F**

In contrast to Figure 4-9 which portrays EMI spectra taken using the line end couplers, the results in Figure 4-10 taken by Tester F rely on signals taken at the common neutral point and thus are not specifically phase resolved. The figure is dominated by high level discharges in the mid-frequency band (1 - 20 MHz) which was traced by Tester F to the isolated phase bus. The clusters of discharges seen at higher frequencies (up to 100 MHz) are also thought to be associated with the problems (loose connection or defective insulation) in the iso-phase bus duct.

Although dominated by discharges outside the generator, the spectrum of Figure 4-10 does also indicate discharge activity within the generator, but at levels which should not cause concern. Of particular interest in the #3 unit was the finding by Tester F that there appeared to be an anomalous pattern of transient pulses associated with the exciter. Figure 4-11 shows an example taken at 250 kHz which depicts missing pulses said to be indicative of open diodes in the exciter circuit. Lack of pulse uniformity may also be indicative of control problems.
Figure 4-12
Marshall #4 EMI data in the frequency range 100 kHz – 500MHz. Tester D.
4.4 EMI Evaluation: Marshall #4

4.4.1 Tester D

Data analogous to that in Figure 4-9 is shown in Figure 4-12 for unit #4. Phase C would seem to be the most active with the strongest discharges occurring between 10 and 20 MHz. As previously, the peak frequencies could be identified and used to filter signals in a PD analysis. No significance was placed on these spectral characteristics.

![EMI Spectrum for Marshall Unit 4 taken by Tester F.](image)

4.4.2. Tester F

Figure 4-13 shows data for Unit #4 which Tester F obtained again from a CT on the neutral. In this case mean levels are much lower since the RF spectrum is not dominated by external noise as it was in Figure 4-10. Some discharge activity is indicated in the mid frequency range and Tester F attributes the PD seen at about 10 MHz to core edge and end-winding discharges, although the indications are that the bars themselves are not loose in the slots. The random noise experienced has been associated in other machines with conductive contamination which would be consistent here with the “grease” referred to in Section 2.
In attempting to learn from the experiences of this program, it is instructive to summarize the findings that were the basic “product” of these measurements. No judgments whatsoever are being made here, since, until units are taken out of service for inspection, speculation made on the basis of this condition monitoring cannot really be tested. Table 5-1. is a matrix containing the findings of the various testing entities (all using somewhat different practices).

Figure 5-1
The first issue which is clear from a study of Table 5-1 is that there is not always agreement on which Phase the phenomena are being observed. As was pointed out earlier, it appears that there has been some confusion in this case over the origins of the synchronizing signal used. However, this is so fundamental that great care needs to be taken. In particular, references taken from sources other than the PTs must be viewed with suspicion since, phase shifts may have occurred in the transmission path (through Y-transformers, etc.). It would appear that in many cases, operators are being left to infer the phasing from the results obtained. This is sometimes quite difficult especially if there is no information on the polarity of the pulses, but only their phase location. [NB pulses will usually be negative in the positive half cycle and vice versa].

The most unifying feature of these tests was the identification of insulator problems or loose connections in the iso-phase bus duct for Marshall unit #3. All those testing this machine (for both PD and EMI technologies) specifically identified this problem with the exception of Tester D. It is ironic that Tester D was the only Company to supplement the electrical discharge testing with acoustic measurements which did show some noise in the bus ducts. However, this was not specifically associated with the large electrical signals registered.

It is unfortunate that the frequency domain results taken by Testers D and F are not really comparable. Not only was the instrumentation used very different, but coupling to the machines was able done at different ends of the winding. The use of line-end capacitive couplers by Tester D has created results which are discriminated by phase, whereas the use of a neutral CT by tester F has generated a composite signal for all three phases. However, comparison of the spectra from the Marshall #3 units (Figures 4-9 and 4-10) does indicate the enhanced levels of signal over a wide frequency band cited by all the Testers. There is also agreement that the peak intensity occurs at about 10 MHz.

It is gratifying, however, to note that the conclusions drawn from both the PD (Figure 3-2) and EMI (Figure 3-3) measurements taken at the Sammis #6 units of Ohio Edison are essentially the same.

### 5.1 Calibration Issues

Another problematical issue relates to calibration. Although discharge detection equipment involving lumped capacitance test objects can be readily and reliably calibrated in terms of apparent charge, by injecting known signals through a coupling capacitor into the measuring system and relating the output to the charge injected [2]. This is not done legitimately in the case of inductive equipment, such as large generators. This is the result of the extensive nature of machines so that pulses travel as waves which are reflected and highly attenuated. The detailed reasoning has been outlined by Stone [3]. As a result, it is normal to express discharge levels in mV, but clearly the absolute level cannot be relied upon since it will depend on gain settings, coupler type, attenuation, etc. Providing, all the variables are kept constant (or accounted for), then relative magnitudes (either between phases, or even between similar machines) are a reasonable way to gauge discharge levels. For this reason many testing companies keep databases to allow this comparison. There can be little doubt that the most reliable policy is to benchmark a machine and then compare any changes occurring in time using the same equipment and technique – see examples in Section 5.5.
## Table 5-1
Matrix of Test Findings

<table>
<thead>
<tr>
<th>Tester</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method</strong></td>
<td><strong>PD LF 2 Freq</strong></td>
<td><strong>PD HF</strong></td>
<td><strong>PD LF</strong></td>
<td><strong>PD LF 2 Freq</strong></td>
<td><strong>Acoustic</strong></td>
<td><strong>EMI</strong></td>
</tr>
<tr>
<td>Sammis  #6</td>
<td>1st Finding</td>
<td>Modest discharge activity in the groundwall of Phase B</td>
<td></td>
<td></td>
<td></td>
<td>Stable condition</td>
</tr>
<tr>
<td></td>
<td>2nd Finding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Action</td>
<td>Re-test in 6 months</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marshall #3</td>
<td>1st Finding</td>
<td>Large discharges center on Phase C associated with busbars</td>
<td>External bus duct discharges in Phase C</td>
<td>Discharges at surfaces in Phase B</td>
<td>Some activity detected</td>
<td>External surface PD in Phase B</td>
</tr>
<tr>
<td></td>
<td>2nd Finding</td>
<td>Source of the external discharges should be determined immediately</td>
<td>Some groundwall degradation, and end-winding discharges in Phase B</td>
<td>Surface PD in Phase C</td>
<td></td>
<td>Exciter circuit problems</td>
</tr>
<tr>
<td></td>
<td>Action</td>
<td>Check bus insulator tightness &amp; Ph B end-winding wear at next outage</td>
<td>Repeat PD test in 6 months. Inspect at next outage.</td>
<td>No significance</td>
<td></td>
<td>Locate &amp; correct bus duct problem. Inspect exciter at next outage</td>
</tr>
<tr>
<td>Marshall #4</td>
<td>1st Finding</td>
<td>Large discharges in Phase C associated with busbars</td>
<td>Loose bus duct insulator, Phases A and B.</td>
<td>Surface PD in Phase C</td>
<td>Some activity detected</td>
<td>Strongest activity in Phase C at 10.5 MHz</td>
</tr>
<tr>
<td></td>
<td>2nd Finding</td>
<td>Degraded stress control coating, and end winding problems on Phase B</td>
<td></td>
<td></td>
<td></td>
<td>End-winding PD No indication of external problems.</td>
</tr>
<tr>
<td></td>
<td>Action</td>
<td>Immediate visual and ultrasonic inspection</td>
<td>Check bus insulator tightness tightness &amp; Ph B end-winding wear at next outage</td>
<td>Repeat PD in 6 months. Inspect at next outage.</td>
<td>No significance</td>
<td>Inspection Recommended.</td>
</tr>
</tbody>
</table>
5.2 Interpretation

Detailed study of the testing conducted at the Marshall plant did, in fact, reveal that there was considerable agreement over the nature of the data recorded. The interpretation, however, was not always the same, despite the fact that the engineers involved were all very experienced. All the commercial entities contributing to this study obtained EMI or PD data and then applied good engineering judgment to the phase-resolved pulse counts or spectral results. This was done using time-honored yardsticks (polarity predominance, phase angles of discharge groups, frequency bands involved, evidence of cross-coupling, etc) and is a method which has served the industry well. However, the extension of these techniques to field engineering staff will need a more formalized method of applying decision criteria to these methods. Some of this activity was started many years ago [4,5] using both expert system inference engines and the application of distillation methods to extract meaningful indices from the raw data. The integrated measure introduced in Figure 3-1 and used by Tester B would be a simple example of this. More recently fractal dimension [6] and discharge stagnation voltage [7] have been advanced as additional measures, but there has been little field experience with them. With computing power now very cheap, this is an obvious way to advance the technology; providing the needed automated interpretation and increased reliability. Research is ongoing on this aspect of detection to augment the expert systems methods being applied in a wider context [8] which will assume greater importance as plant operators demand location information from tests as well as just a condition assessment. It is anticipated that neural network and other pattern recognition methods [9] will find application in the interpretation process.

5.3 The Use of RTD elements as PD sensors

Figure 4-5 illustrated the use of RTD temperature measuring elements as sensors for partial discharge measurements which has recently been advocated [10]. This has become a controversial issue and has recently attracted some attention in the technical literature where it has been criticized [11].

5.4. EMI and PD Comparison

In discussing the merits of PD and EMI for insulation assessment, it should be recognized that, although PD is a time-domain measurement and EMI measures activity with a frequency scan, both techniques are still looking at the same phenomenon – the high frequency currents that flow as the result of electrical (partial) discharges occurring within the structure. A recent comparison of the EMI method and high-frequency PD detection by Timperley [12] has concluded that they exhibit the same sensitivity to discharge activity generated in laboratory tested stator bars. However, the way in which the signals are captured and measured in field tests often changes the utility of the measures used. Two major factors can be identified:

- Many PD measurements are taken with detection systems which provide gating to discriminate against external interference. In this way, the signals obtained are designed to represent the condition of the machine without the complication of corruption from external sources. On the other hand, some proponents will argue that the external “interference”
rejected in such circumstances carries useful information about potential problems in related external components (isolated phase bus insulator failure, arcing alternator slip rings, etc). Indeed, the bus duct problems identified at Marshall by most of the testers is a case in point. Clearly, interference for one school of thought is signal for the other.

- PD measurements may be taken over different frequency ranges. Those who advocate the use of high frequencies have the substantial advantage that the measurements are much less likely to be corrupted by external interference in comparison with techniques that rely on broadband detection. However, there is a price to be paid in terms of sensitivity to highly attenuated signals from sites which are a long way from the coupler used. The use of high frequencies also has the advantage that a low capacitance coupler (» 100 pF) will suffice. The counter argument is that the susceptibility of the lower frequencies to interference can be compensated by signal processing and other computer-based techniques which may allow the best of both worlds. This program will try to address this issue in the future by contrasting the results obtained by both approaches.

5.5 Trending studies

The greatest benefit for a generator operator of either PD or EMI analysis is the ability to examine the degradation of a unit with respect to a baseline signature. Figure 3-2. is an example of the application of this process. A pulse height analysis is compared with an earlier benchmark at the Sammis #6 unit and indicates little change in the condition of the unit. In contrast, Figure 5-1. shows two phase-resolved PD plots for Marshall #3 taken 15 months apart and clearly depicts that there are now TWO sources of activity of very different magnitudes coupled to all three phases – note the different scales of Figure 5-1(a) and (b). The same tester was responsible for both of these measurements and thus one may assume that they were taken using the same equipment and methodology. Indeed, the changes seen here resulted in a different diagnosis and recommended action plan.

5.6 Best Practices

Discharge detection in both the frequency and time domains has evolved and been adapted to meet the needs of specific industrial situations. While the testers in this study are using the same basic principles, there are some differences in approach. The issue of the measurement bandwidth has been addressed in Section 5.4, but it is also instructive to examine other practices. Essentially, anything that assists in extracting additional or supplementary data from the system can only improve the picture that emerges.

- It is not always easy to get unambiguous information from the signatures available at the machine terminals since the signals are often corrupted by noise. Perhaps the most effective way to reduce noise is to use two sets of couplers per phase and then use time-of-flight methods to discriminate against pulses entering from outside the machine. Although this was not done at the Marshall site (where the single set of couplers were positioned some 10 m from the generator terminals), it certainly would have probably permitted the testers to associate the high level discharges with the isophase bus if that is, indeed, the location. Table 5-1 indicates that this was not an issue over which there was agreement.
The use of other methods to reduce the impact of noise can be useful. Techniques such as setting a threshold for PD counting, establishing a background frequency scan to identify FM broadcast stations etc. are effective. For example, it is clear from Figures 4-10 and 4-13 that there are several sources of both power line carrier (~ 100 kHz) and HF transmitters (~ 100 MHz) which must be identified and eliminated from the EMI spectrum.

One of the Testing Companies undertook an acoustic scan of the bus ducts. While this scan did not produce an unambiguous result, it was able to detect activity, and would seem to be a quick and worthwhile additional test.

Discharge characteristics are known to change as a result of both loading and power factor changes providing additional information. Systems which are able to monitor activity over a period of time in which such changes take place clearly add another dimension to the diagnostic technique.

To different extents, some of those testing at Marshall used a “combined” analysis – a PD analysis undertaken in a specific frequency interval. Although it was not clear from these tests that much benefit accrued from this practice, some defects have been associated with particular frequency intervals. Consequently, selecting particular frequencies can provide some information on the type (and thus location) of discharges. Clearly this requires either a reliable and comprehensive database or a very experienced operator.

It is evident that both PD and EMI signatures are complex and often difficult to interpret. This is particularly so in the case of measurements in the frequency domain where the interpretation of the results is currently critically dependent on the experience of the individual taking the measurements. To some extent, all those doing such testing select indices to describe the characteristics or severity of the condition being investigated - even those who describe a test in terms of a peak magnitude are unwittingly doing that. The distillation of the characteristics into meaningful parameters is seen as a useful benefit, and a necessary first step on the road to the greater use of machine intelligence in the diagnosis of machine problems. The need for reliable methods of data interpretation is seen as perhaps the greatest impediment to the more widespread use of this technology.
REFERENCES


References


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